Southern Africa Validation of EOS (SAVE)
Status Report

http://modarch.gsfc.nasa.gov/MODIS/LAND/VAL/terra/privette

06 June 2000

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Et al.

a) Project Objectives

In the period since the last Status Report (14 Sep. 1999), SAVE transitioned from the procurement and deployment phase into active measurement phase.

b) Tasks Accomplished

• 2nd SAVE/SAFARI Field Campaign (February/March, 2000)

SAVE conducted its second significant field effort along the Kalahari Transect, as part the second SAFARI 2000 campaign. Together with local and international collaborators, SAVE investigators collected abundant soil, vegetation and atmospheric data at one site in western Zambia and four sites in Botswana, roughly following a north-to-south transect. Details of the measurements and sites are in the appended Summary Report (submitted to the *EOS Earth Observer*). Participating SAVE personnel included Privette (GSFC), Scholes (CSIR/Pretoria), Pinheiro (GSFC), Hanan (CSU), Caylor (UVA) and Dowty (UVA). Four student researchers from Ranga Myneni's team (MODIS LAI/FPAR product) actively participated as well. Scholes, Privette and Caylor helped organize and lead the campaign. Manuscripts for a special issue on the wet season campaign are due in November 2000.

• 1st SAVE/SAFARI Field Campaign (August, 1999)

SAVE continues to reduce and analyze data collected during the first SAFARI dry season campaign in 1999. These data include LAI, % cover, soil moisture and temperature profiles, infiltration rates, surface albedo, surface spectra, leaf water potential, growth and decay rates of the boundary layer, incoming solar radiation, aerosol sampling, and thermodynamic profiles of the troposphere. Several publications are underway related to these data.

• Year-round measurements

Besides field campaigns, SAVE is collecting year-round measurements at the two core sites (Skukuza and Mongu). Since 8/99, SAVE has collected LAI, aerosol, and soil temperature and moisture data at Skukuza, and aerosol data at Mongu. Excellent data were collected through the transition from dry season to wet season. The latter was particularly pronounced this year.

• SAVE Implementation Plan

An updated Implementation Plan (V 2.0) was completed and disseminated in December 2000. It is available on the WWW site, which itself has been significantly updated.

• Tower construction

The towers are installed, instrumented, and performing as planned. Specifically, the 33 m Mongu, Zambia tower hosted a complete CO2/energy eddy covariance system during the SAFARI 2000 wet season campaign (March 2000). Although the eddy covariance instrumentation was removed following the campaign, the tower is still being used for ongoing albedo measurements (NIR and shortwave). The 22 m tower in Skukuza, South Africa is currently outfitted with an eddy covariance system as well as albedometers. The eddy covariance system was installed by Hanan (SAVE Co-I) and Scholes (SAVE Co-PI) and was funded by the NASA TEP. After some processing, the albedometer data will be used to validate the MODIS and MISR albedo products, while the eddy covariance data will be used to validate the MODIS NPP product.

• **SAFARI 2000 Collaboration**

Besides helping lead the SAFARI Wet Season Campaign, SAVE took a fairly active role in helping NASA Code IY develop the Letters of Agreement and Memoranda of Understanding for SAFARI. These have been slow in developing but appear on track at this time.

Two of the four SAFARI field campaigns are now complete. SAVE will participate in the two remaining ones, including:

- Aug/Sept. ’00 Major dry season (fire) regional campaign (with NASA ER-2)
- Nov/Dec. ’00, Miombo Transect (Zambia to Mozambique) mobile campaign

• **Ozonesonde releases (Collaboration with SHADOZ/SAFARI)**

In spring, 2000, SAVE purchased 37 ozonesonde/radiosonde for the South African Weather Bureau in Irene, South Africa, to augment their launches between Feb-July, 2000 (doubled frequency of soundings -- now 1 to 2 a week). SAVE/SHADOZ will continue to work with this site as begins releasing up to three times per week from July through December 2000. Thompson and Witte tentatively plan to release daily ozonesondes for about two weeks in September at Mongu, during the SAFARI 2000 dry season campaign. This work will be coordinated with the intensive aircraft grab sampling and remote sensing occurring in the region, as well as the prescribed biomass fires to be conducted by Darold Ward (EOS Validation Investigator). Finally, Thompson participated in the WMO sponsored Dobson Intercomparison Workshop in Pretoria in April, 2000. Extensive planning for the SAFARI dry season campaign was conducted at this time. Thompson held a special session of posters and papers of SHADOZ analysis in the Atmospheric Sciences section of AGU, and a SHADOZ workshop of Co-Is during this period.

• **Collaborating and Support Personnel**

A. Pinheiro (Univ. of Lisbon, NASA GSFC) is continuing to lead MODIS surface temperature and hydrology validation activities in southern Africa. In March, she deployed a profile of temperature and moisture probes in Mongu to complement her similar profiles in Skukuza. The latter provided continuous data from August 1999 through January 2000, before the data logger was inundated with water due to excess precipitation. She has begun a reparameterization effort of the SiB2 soil model in an effort to understand early signs of drought and to help validate MODIS NPP and hydrology products.

N. Khatib (Univ. of Colorado) continues to collaborate with SAVE through a GSFC University Programs Fellowship. Khatib will be helping collect LAI/FPAR data at sites in

Colorado, Iowa and Africa. He is also ingesting AVHRR data and evaluating a corn productivity model for use in Africa.

SAVE collaborated extensively with various researchers and projects during the August 1999 field campaign. Particularly useful collaboration was developed with Gareth Roberts (Univ. of London, land cover type/change), Si-Chee Tsay (GSFC, aircraft spectral imaging and atmospheric radiation measurements), and Luanne Otter (CSIR/LEAD, hydrological measurements). SAVE is working closely with two site technicians in region, Musa Mazundla (Skukuza) and Mukufute Mukelabai (Mongu). Significant logistical support was provided by collaborators Harold Annegarn, Stuart Piketh and Lackson Marufu (WITS) and Holger Eckhardt (Kruger Park).

• **Instrument procurement**

Instrument procurement is essentially complete. Some replacement or backup instruments are being procured as needed (e.g., in cases where regular recalibration is needed such that the data stream can continue uninterrupted).

• **Instrument development**

The simple up and downlooking red/NIR high-speed sensors are still under development. This will allow estimation of grass NDVI/LAI, and measurement of overstory fractional cover.

We recently upgraded the SAVE version of the MQUALS package (MODIS Quick Airborne Looks) to include real-time GPS locational information. We field-tested this package at the Konza Prairie last July, however we have not yet mounted it to an aircraft in southern Africa (primarily due to time constraints).

Privette, together with Code 553 and AERONET personnel, was funded by GSFC DDF to develop an advanced sunphotometer to eventually replace the current CIMEL design. We have developed a 14-band sensor and have fit it to a CIMEL robot. A laptop computer is currently used for both operating the instrument and storing the data. We expect to deploy this instrument in Mongu for the SAFARI dry season campaign.

• **Data procurement**

We continue to receive excellent support from various "tasked" data systems (e.g., Landsat 7, ASTER, IKONOS and MISR) for regular collection of scenes over SAFARI 2000 Core Sites. Data from each of these systems were collected during the wet season campaign. We continue to work with Jim Tucker's group to develop 1 km AVHRR data products and a "quick-look" aircraft planning product over the region. Early MODIS data were largely contaminated with clouds during the wet season campaign, however the atmospheric correction mosaics look fine. We are in frequent communication with the MODLAND team and will collaborate with several investigators in early product validation. SeaWiFS data are currently being archived online for Mongu and Skukuza through the EOS Land Validation Core Site initiative.

• **Data protocols and archiving**

We are helping lead the GSFC effort to gather, document, disseminate and archive SAVE/SAFARI data via CDROMs (J. Nickeson and D. Landis, POCs). This activity formally began in May, 2000, and has forced many decisions concerning SAFARI data priorities and formats. Target date for the first SAFARI CDROM, to include IFC1 and IFC

2 field data plus various remote sensing data sets, is late 2000. These CDROMs will be mass produced and sent to investigators in the region. An important planning meeting for data issues will be held at the Univ. of Virginia on 6/13-16/00. We continue to work with the ORNL DAAC in developing a master plan for data archiving and synthesis.

• CEOS WGCV Land Product Validation Subgroup

A subgroup of the CEOS Working Group for Calibration and Validation was recently initiated and held its first meeting in Ispra, Italy (5/26-29/00). Excellent discussions were held concerning plans for Level 2+ land product generation and validation by the international participants. The priority issues for the next 12 months are to develop definitions and guidelines for field validation, as well as conduct a pilot LAI satellite product intercomparison for a series of test sites. This will not include any new field activities, but will leverage already-planned activities. This has the potential to be of significant value to EOS validation. Privette is co-chairing this subgroup with Stephen Dech (DLR/Germany). The next meeting of WGCV is in Gaithersburg, MD, in October. A LPVS meeting will be sponsored near that time.

• Jornada/PROVE Special Issue of Remote Sens. Environ.

A special issue of Remote Sensing of Environment, dedicated to EOS product validation, will be published in August/September, 2000. This issue will contain 12 articles concerning the EOS Prototype Validation Exercise (PROVE) near Las Cruces, NM, in May 1997. The MODIS, MISR, ASTER and Landsat 7 teams participated and were supported with data from ER-2, POLDER and AVHRR. Privette is the guest co-editor of this issue.

• Issues

Formal coordination among Validation Investigators (e.g., meeting) may facilitate more useful results when Terra data starts flowing

• Meetings/Presentations/Posters (Privette, Pinheiro only)

- Kalahari Transect Planning Meeting, UVA, 10/22
- EOS Validation presentation to ISLSCP II workshop
- ORNL DAAC UWG meeting 1/7/00, Herndon, VA
- Cape Town 2000, 28th Int. Symp. Rem. Sens. Environ., 3/27-31/00, Africa
- SAFARI 2000 Seminar, Univ. Botswana, Gaborone, 3/20/00
- Remote Sensing and Hydrology 2000 Conference, Sante Fe, March 2000 (Pinheiro)
- Amer. Geophys. Union, Spring Session, Washington, DC May, 2000 (Pinheiro).
- SAFARI 2000 Data Dissemination Planning Meeting, UVA, June 2000

• Publications (1998-99)

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[¥]Pinheiro, Tucker, Entekhabi, Privette, and Berry (2000), Assessing the relationship between surface temperature and soil moisture in southern Africa, *Proc. Of Remote Sensing and Hydrology 2000*, Sante Fe, in print. ([¥]This peer-reviewed manuscript is in Appendix III).

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White, M.A., G.P. Asrar, R.R. Nemani, J.L. Privette and S.W. Running (1999), Measuring fractional cover and leaf area index in arid ecosystems: digital camera, radiation transmittance and laser altimetry results, Remote Sens. Environ., in print.

APPENDIX 1. SAVE-sponsored year-round data collection

Parameter	Location	Start	Frequency	SAVE Lead
Soil moisture	Skukuza	8/99	Continuous	Pinheiro
Soil temperature	Skukuza	8/99	Continuous	Pinheiro
LAI/ %Cover	Skukuza, Mongu	8/99	Periodic, Once	Privette
Surface albedo	Skukuza	8/99	Continuous	Privette
Aerosol AOT	Skukuza, Mongu	7/98	Continuous	Swap
Aerosol source attribution	Skukuza, Mongu	7/99	Continuous	Swap

APPENDIX 2.

Report on SAFARI 2000 Wet Season Ground Campaign – March 2000

May 25, 2000

Summary

An international group of researchers completed an intensive field campaign in Botswana and Zambia between February 28 and March 18, 2000. This campaign represents one of the main activities of the Southern Africa Regional Science Initiative 2000 (SAFARI 2000). This initiative is studying the regional land-atmosphere system with emphasis on terrestrial emissions (biogenic, pyrogenic and anthropogenic), atmospheric modification and transport of these emissions and the consequences of subsequent deposition on the biogeochemistry of the regional ecosystems. The field campaign summarized here consisted of ground and tower-based measurements. The main objective was to bring together a diverse group of researchers to characterize land surface processes and land-atmosphere exchanges during the growing season at a broad range of land cover types in the region. The participants represented institutions in the region, in the US and in other overseas countries. The research activities spanned plant physiology, ecological and hydrological processes, meteorology and atmospheric aerosols and ground validation of EOS data products.

The field sites were organized around the Kalahari Transect (KT) [Chanda *et al.*, 1998; Ringrose and Chanda, 2000; Scholes and Parsons, 1997]. This is one of the IGBP Terrestrial Transects designed to study global change issues using a coordinated set of field sites [Steffen, 2000] covering large areas (on the order of 1000km) and spanning significant variation in a major environmental or land-use factor. The KT spans a large rainfall gradient in an area of uniform soils, the Kalahari sands, albeit with some local soil variation associated with pans and subsurface duricrusts. Conceptually, the KT extends from equatorial forest in Congo-Brazzaville to subtropical, arid shrubland of the Kalahari desert in south-western Botswana and adjoining areas of South Africa and Namibia, although the northern portion has not yet been studied as part of the KT.

The campaign started on February 28 in Mongu, Zambia with a group of 18 researchers. This group proceeded to four sites in Botswana where they were joined by researchers from the University of Botswana, the Botswana Meteorological Services and Ministry of Agriculture. The campaign ended on March 18 at Tshane, Botswana. A group of students from the University of Botswana participated in various activities at the Tshane site. They were trained in the use of a number of field techniques and instruments and participated in data collection. Dr. O.Totolo, the lead coordinator for the KT based at the University of Botswana, also visited the group at Tshane. On March 20, a seminar was held at the University of Botswana where the participants discussed their work and shared preliminary findings. The field sites in Botswana had received above-average rainfall at the time of the campaign. This was associated with tropical cyclone Eline, an Indian Ocean storm which led to widespread flooding in many areas of the region.

A large amount of data and samples were collected during the campaign. Some data will be immediately and openly available. Remaining data will be made available as sample analysis and data processing is completed. This report gives an overview of the various field activities and points of contact for more information.

Sites

Figure 1 shows the location of the five field sites and the extent of soils dominated by Kalahari sands as delineated in the FAO soils dataset [FAO, 1995]. All sites are on the southern African plateau with elevation on the order of 1000 meters. The sites were selected to span a significant portion of the rainfall gradient in the region.

Kataba Forest *-15.438 South; 23.253 East*

Activites at this site were coordinated by Mr. Mukufute Mukelabai of the Zambian Meterological Deptartment. The site is in a forest reserve approximately 20km south of Mongu. It is one of the core EOS validation sites where a permanent 33m tower has been erected. The vegetation cover is Kalahari woodland dominated by *Brachystegia spiciformis.* Mean annual rainfall (interpolated from nearby stations) is 879 mm.

Pandamatenga Agricultural Station *-18.655 South; 25.500 East*

This site is approximately 100km south of Kasane, Botswana on the Francistown road. Vegetation cover is an open woodland with dominant tree species that include *Ricenodendron rautanenii*, *Baikiaea plurijuga* and *Burkea africana*. Mean annual rainfall (interpolated) is 698 mm.

Maun *-19.923 South; 23.594 East*

Dr. Elmar Veenendaal of the Harry Oppenheimer Okavango Research Centre (HOORC), located in Maun, Botswana, hosted the activities at this site. Dr. Veenendaal operates a permanent flux tower in collaboration with the Max Planck Institute at a site approximately 20 km northeast of Maun. Activities were focused in an area approximately 3 km from the permanent flux tower but some sampling was duplicated at the permanent tower site for comparison. Vegetation cover at both sites is mopane woodland (*Colophospermum mopane*) although the main area of focus has lower tree heights than the permanent tower site and patches of *Terminalia sericea* thicket. Mean annual rainfall at Maun is 460 mm.

Okwa River Crossing *-22.409 East; 21.713 East*

This site is located where the Trans-Kalahari Highway crosses the Okwa River, approximately 80 km south of Ghanzi, Botswana. This site has some topographic variation and soil characteristics which distinguish it from the surrounding landscape. Vegetation cover is an open shrubland with scattered trees. Dominant species include *Acacia mellifera* and *Grewia flava*. Mean annual rainfall (interpolated) is 407 mm.

Tshane *-24.164 South; 21.893 East*

This site is located approximately 15 km south of Tshane, Botswana. The University of Botswana has a number of research activities focused in this area. The vegetation cover is open savanna dominated by *Acacia luederitzii* and *Acacia mellifera.* Mean annual rainfall at Tshane is 365 mm.

Field Activities

The activities are summarized here by category. The contact names listed represent only a subset of the participants, but they can direct inquiries to others when appropriate. All participants are listed at the end of this document.

Meteorology

A team from a number of Botswana Meteorological Services offices recorded standard meteorological observations (wet and dry bulb temperatures, wind speed and direction) at 30 minute intervals at each of the sites within Botswana. Instruments were setup immediately adjacent to the site where the other groups were sampling. (Contact: Edward Bojang,)

Meteorological data (30 minute averages) were also recorded from the portable tower used to measure canopy fluxes. (Contact: Todd Scanlon).

Leaf and Canopy Radiation

A number of instruments were used at each site to characterize canopy radiation and canopy properties, including leaf area index. Data was collected at 93 sample points over three parallel transects at 25 meter intervals. The transects were 750 meters long and separated by 250 meters. Spectral properties of leaves and soil were also measured.

Measurement	Instrument	Contact
Canopy Properties (canopy transmission, leaf area, leaf orientation and clumping, % cover)	Licor LAI-2000	Bob Scholes, Jeff Privette, Yujie Wang
	TRAC	Jeff Privette
	Decagon Accupar	Bob Scholes, Yujie Wang
	Nikon Digital Hemispherical Camera	Gareth Roberts
	ASD Field Spectrometer	Jeff Privette
	Kipp and Zonen CM14	Jeff Privette
	Kipp and Zonen Net Radiometer (tower mount)	Todd Scanlon
Component Spectra (e.g. leaves, soil), canopy transmission spectra	ASD Field Spectrometer, Licor 1800 Spectrometer	Yujie Wang

Vegetation Structure/Composition

Various techniques were used to characterize the vegetation at a range of spatial scales. In some cases the same parameters were sampled with contrasting techniques. The table below gives a simple summary.

Parameter	Technique	Contact
Tree/Shrub Cover/Basal Area and Composition	Stem map	Kelly Caylor
	Line transects	Jerry Ramontsho, Chris Feral
	Circular sample plots	Bob Scholes
	Spherical Densiometer	Kelly Caylor, Peter Frost

Parameter	Technique	Contact
Landscape-scale Composition/Structure	Line transects	Susan Ringrose
Grass Composition	Line transects	Chris Feral
	Circular sample plots	Bob Scholes
Grass Biomass	Quadrat clipping	Kelly Caylor
Root Distribution	Soil pit profile/root excavation	Martin Hipondoka
Tree Age Structure	Tree Cores	Kelly Caylor

Leaf Processes

The dominant species at four Botswanan sites were characterized ecophysiologically. CO_2 response and light response of photosynthesis and dark respiration were measured at three different temperatures spanning 10°C (i.e. 25, 30 and 35°C) using a LiCOR 6400 Portable Photosynthesis System. Derived parameters include stomatal conductance, V_{cmax}, J_{max}, quantum efficiency, CO_2 and light compensation points. Also leaf size was measured in order to determine leaf specific area and mass. Also, leaf dimensions and specific leaf area of dominant species were determined at the Botswanan sites. (Contact: Guy Midgley).

Hydrocarbon emissions were sampled at the leaf level, as described Biogeochemical Cycling. (Contact: Luanne Otter).

Canopy Fluxes

Canopy energy, water and carbon fluxes were measured from tower-based sensors at all sites except Pandamatenga. One set of sensors was placed on the permanent tower at Mongu for the duration of the campaign while a mobile tower system was used for short-term data collection (2-3 days) as the team moved through the other sites. The data collection period at Mongu was March 1 to March 24.

An identical set of instruments was deployed on both the Mongu and the mobile tower systems. This included the following instruments: Licor 7500 CO_2/H_2O Analyzer, Hygrometer, 3D Sonic Anemometer, Kipp & Zonen net radiometer, air temperature/humidity probe and an infrared thermometer measuring surface temperature.

In conjunction with the mobile tower only, open and under-canopy patches were instrumented with: soil heat flux plates (5cm depth), TDR soil moisture probes (0-30 cm) and soil temperature thermocouples (2.5 and 7.5 cm).
At the Maun site, the mobile tower was located approximately 3 km from a permanent flux tower in an area with contrasting vegetation structure. The permanent tower is operated by Dr. Elmar Veenendaal of the Harry Oppenheimer Okavango Research Centre (University of Botswana) in collaboration with the Max Planck Institute. A comparison study will explore variability in fluxes in these different landscape units over the period in which the mobile tower was in operation. (Contact: Todd Scanlon)

Atmospheric Aerosols

A handheld multispectral sun photometer was used at each site to assess atmospheric radiative characteristics. Measurements were taken throughout the day except when prohibited by cloud cover. (Contact: Mukufute Mukelabai).

Daytime total suspended particulate (TSP) samples were taken at each site. A high volume pump was used to draw air through a glass fiber filter for 8 to 12 hours at a rate of approximately $1.4 m^3/min$. Stable isotopic analysis will be performed on the collected samples to study nutrient deposition at each site. (Contact: Kaycie Billmark).

Biogeochemical Cycling

Specific biogeochemical processes were assessed with the techniques indicated in the table below. Plant and soil samples were collected for chemical and isotopic analysis as described below.

Processes	**Technique**	**Replicates**	**Contact**
N mineralization	*In situ* isotope dilution method: soil extracts to be analyzed in the laboratory.	3 replicates of composited soils (n=8 subsamples) under the canopy and 3 within the canopy.	Julieta Aranibar
Nitrification	*In situ* isotope dilution method: soil extracts to be analyzed in the laboratory	Same as above	Julieta Aranibar
Nitrogen fixation by soil microorganisms-soil crusts	*In situ* acetylene reduction assay: gas samples to be analyzed in the laboratory	8 replicates in all sites except Tshane, where 15 replicates were analyzed	Julieta Aranibar
Hydrocarbon emissions	Absorbent traps were used to collected hydrocarbon emissions from leaves and these will be analyzed by GC-FID and MS in the laboratory	2 replicates of about 4 dominant species at Mongu, Okwa River crossing, Tshane	Luanne Otter
NO_x emissions	Soil samples were collected and NO production and consumption rates, temperature and soil moisture response curves for NO will be measured in the laboratory using a chemiluminescence NO/NO_2 analyzer	3 replicate soil samples from each site were collected	Luanne Otter

Nitrogen cycling processes were analyzed, with a combination of *in situ* experiments and soil and plant sampling for laboratory analysis. N mineralization, nitrification and N fixation were analyzed at all the sites except Pandamatenga. Mineralization and nitrification, as well as soil and plant sampling, were also analyzed at additional sites in Maun and Tshane, with different grazing intensities. Tree shrub and grass samples of all the common species were collected for isotopic ($\delta^{13}C$ and $\delta^{15}N$) and nutrient analysis (%C, %N, %P). Soils under different functional types of plants and at different depths (0-5, 5-10, 10-15, 15-20, 20-30 cm) were collected for the same analysis, and KCl soil extracts were prepared in the field in order to analyze isotopic composition of ammonium and nitrate. The data will be available after sample analysis in the laboratory. (Contact: Julieta Aranibar)

Leaf, twig, root and soil samples were collected at the Maun, Okwa River and Tshane sites for each of 4 vegetation types, grasses, trees, shrubs, forbs. Three additional sites representing different intensities of land use were also sampled, including a *Colophospermum mopane* cluster inside the Botswana veterinary fence (low cattle grazing pressure), a wild sage-dominated field near Maun that has sustained heaving grazing and encroachment of an introduced species, and a cattle station approximately 20km from the Okwa River crossing. These samples will be analyzed for resident organic and mineral nutrients in the soil and their accumulation/availability in the adjacent plants. Data from the three research sites should provide insight into the natural variation of nutrients within plants along the rainfall gradient and will be compared to data from beyond the veterinary fence, the wild sage field and the cattle station sites to look for differences that may be attributable to increasing land use intensity. (Contact: Chris Feral).

An attempt will be made to isotopically trace deposited nutrients from atmospheric aerosol (TSP) samples through the soil profile and into the vegetation. Ideally, we will be able to identify a unique isotopic signature that will be retained as nutrients are cycled through the system. With further study in conjunction with the SAFARI program, sources of nutrient inputs to the entire Kalahari region will be traced. (Contact: Kaycie Billmark).

<u>Soil Hydrology</u>

A profile of soil moisture and soil temperature sensors was deployed approximately 30 meters North of the Mongu flux tower. The profile includes five TDRs (Campbell Scientific CS615) and three thermisters (Campbell Scientific 107L) placed at the following depths: 5 cm, 15 cm, 30 cm, 60 cm and 125 cm. The profile also includes a soil heat flux plate (Campbell Scientific HFT3) deployed at 10 cm depth. Measurements are being taken every ten minutes and averaged and stored in a Campbell Scientific CR10X datalogger every half-hour. The profile is expected to be left in place for the next two years.

Soil samples were collected at different depths (at the profile location) in order to determine bulk density, total organic matter content, texture, particle size distribution and cation exchange capacity. Seven additional surface soil samples were collected in the area (with location randomly selected) and will be subject to similar lab characterization.

Three main soil layers were identified in the profile area:

Layer Depth	**Characteristics**
0-45 cm	white sandy soil, presence of large amount of fine roots (approximately 50% of exposed area)
45-75 cm	yellowish sandy soil, presence of small amount of roots (mostly thick roots covering about 10% of exposed area)
75-125 cm	dark yellow sandy soil (presence of iron oxides), with very little visible roots (about 2% of exposed area)

(Contact: Ana Pinheiro).

Soil moisture at 0-30 cm depth was measured in conjunction with the portable flux tower measurements with TDR probes. Thirty minute average values were saved over the duration of flux tower sampling at each site (both the portable flux tower and the permanent tower at Mongu). (Contact: Todd Scanlon).

Spatial variation in surface (0-30 cm) soil moisture was characterized over approximately one hectare at the Mongu, Pandamatenga and Okwa River sites. A handheld TDR probe was used on a regular grid of points. (Contact: Kelly Caylor).

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Sponsors

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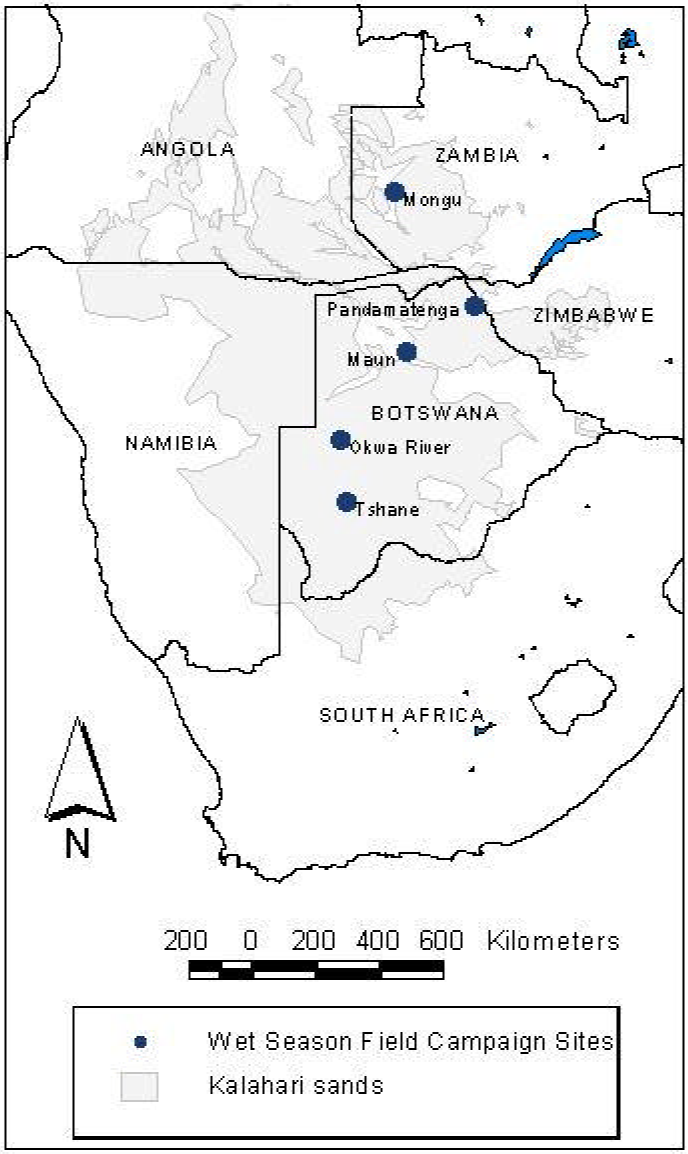

FIGURE 1
Map of field sites and the extent of Kalahari sands as delineated in the FAO Soil Map of the World.

APPENDIX 3

Assessing the relationship between surface temperature and soil moisture in southern Africa

Accepted in

Proc. Of Remote Sensing and Hydrology 2000

(A peer-reviewed publication)

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Abstract Droughts have important implications for the natural and socio-economic environments of southern Africa. An understanding of the relationship between soil moisture content and vegetation condition is necessary to predict the impact of those events. In this paper we proposed a methodological approach for early drought prediction. We hypothesize that the amplitude of the diurnal temperature cycle of a vegetated surface, determined based on remote sensing measurements, can indicate soil moisture content and vegetation condition. We present a preliminary analysis of three months of soil moisture and temperature data collected at Skukuza, South Africa, a core test site of SAFARI 2000. The results support our basic hypothesis yet suggest that further work is required to better understand the coupling of these parameters. SiB2, a common soil-vegetation-atmosphere-transfer (SVAT) model, will be adapted for this purpose.

INTRODUCTION

Much of southern Africa is semi-arid, where vegetation structure and biomass production are controlled by soil water availability, which is in turn mainly a function of the precipitation regime and the soil properties. A better understanding of the southern African ecosystems is necessary to predict soil water availability and minimize the effects of droughts. Knowledge of the coupling between vegetation condition and water availability is possible through the analysis of long temporal data sets covering periods of wet, normal, and drought conditions. We define drought as a soil moisture deficit in the root zone that leads to lower biomass production than would occur under non water stress conditions. Water stress occurs when a plant's demand for water exceeds the plant available soil moisture level.

In this paper we present a preliminary analysis of three months of ground data collected at the Skukuza (South Africa) study site, a core site of the Southern African Regional Science Initiative (SAFARI 2000). This is a large, collaborative research program, which aims to understand the interactions between the atmosphere, the land and the people in southern Africa. In the present paper, we focus on the empirical relationship between soil temperature and moisture. Although many factors affect soil temperature near the surface, the data suggests a high linear correlation between the diurnal soil temperature range and moisture when averaged over a period of 15 days. Cloudy conditions also appear to impact soil temperature significantly.

We are modifying SiB2 to study the feedback mechanisms of this system. Using model results, we will later exploit the relationship between soil moisture and canopy temperature to predict and assess droughts with satellite thermal measurements. This relationship has been extensively explored in previous studies (Carlson *et al.*, 1981; Owe & Van De Griend, 1990; Bastiaanssen *et al.*, 1997).

METHODS

The temperature of the land surface components is determined by the balance of the available solar energy and its conversion to other forms of energy. Measurements of temperature, and temperature variations, can provide information about the target's properties and environment (Short & Stuart, 1982). The variation for the surface temperature, at a given layer, assuming a diurnal frequency for the variation of the heat flux

$$1/2\Delta T = \frac{A_G}{P\sqrt{\omega}}$$

with oscillation amplitude of A_G, can be determined by equation 1 (Castelli *et al.*, 1999), where ω is the period of heating/cooling cycle (assumed to be 24 hr in the Earth) and P is the thermal inertia.

(1)

The thermal inertia, or resistance of a material to temperature change, can be expressed as:

$$P = \sqrt{\rho C_s K_s} \qquad (2)$$

where K_s is the thermal conductivity and $\rho_s C_s$ is the volumetric heat capacity.

The heat capacity and thermal conductivity of water are substantially greater than that of soil porous media (Castelli *et al.*, 1999). Therefore, soil thermal inertia increases with soil water content. However, for a layer closer to the surface, the assumptions inherent to equation (1) break down since other variables (e.g. wind velocity, cloudiness, air humidity) affect soil heating and cooling. Therefore, at the surface, soil temperature and water content are not expected to show a strong linear relationship.

In this study we assess the relation between soil temperature and thermal inertia, and consequently temperature's dependency on thermal conductivity and heat capacity. Clearly because the latter variables are functions of soil moisture, we expect a relationship between soil temperature and moisture, although its form is not known.

EXPERIMENT

The Skukuza (25.02 S, 31.5 E) core site of SAFARI, located at Kruger National Park, South Africa, is an upland savanna 300 meters above sea level, dominated by *Combretum apiculatum* (red bushwillow), and laying in a shallow (less than 50 cm) and stony soil (Gertenbach, 1983). The rainfall average is 546 mm per year and the mean windspeed is 2 m/s (Scholes, personal communication). During the First Intensive Field Campaign (IFC1; August/September 1999) of SAFARI 2000, we deployed two profiles (A and B, 8 m apart along the East-West axis) of soil moisture and soil temperature sensors. Our sensors included *Campbell Scientific* CS615 soil time domain reflectometers and *Campbell Scientific* 107L thermisters. Profile A included three reflectometers and three thermisters at depths of 5, 15, and 30 cm. Profile B includes four reflectometers at depths of 5, 15, 30, and 40 cm, and two thermisters at depths of 5 and 30 cm. The CS615 reflectometer provides an indirect measurement of soil water content by monitoring the soil dielectric constant (Campbell Scientific, 1996). There are two soil properties which affect the response of the CS615 to changes in water content. High clay contents (greater than 30%) and high electrical conductivity (greater than 1 dS/m) require calibration adjustments. Since the clay content of soil at our site is about 12% (Venter, 1990) the former effect was neglected. However, a calibration adjustment was applied to compensate for the electric conductivity (1.8 dS/m; Venter, 1990) using equation 3:

$$\theta_v(\tau) = -0.207 + 0.097\tau + 0.288\tau^2 \qquad (3)$$

where θ_v is the volumetric water content on a fraction basis, and τ is the CS615 output period in milliseconds. Measurements were made every 10 minutes, averaged and stored in a Campbell Scientific CR10X datalogger each half-hour.

RESULTS AND DISCUSSION

We focus on data collected in the first three months (September-November, 1999) after sensor deployment. First, we assessed the consistency of data between the two profiles (A and B) by correlating like data at each depth. The soil moisture and soil temperature data showed a very high linear correlation (Pearson) (see Table 1). No obvious justification was found for the comparatively lower correlation between the soil moisture data at 30 cm.

Next, we assessed the response of the soil moisture content to rainfall events, using rainfall data collected at the Skukuza meteorological site, located approximately nine kilometers NE-E of the study site. The daily mean soil moisture and rainfall data collected from day-of-year [DOY] 244 to 334 are shown in Fig. 1. This period overlaps with the transition from the dry to the raining season. During the first rain events of the season, a very limited amount of water reaches the deepest layer (40-cm). The vegetation roots are predominantly distributed around 30 cm depth (for *Combretum*) and 10 cm (for grass) (Scholes, personal communication), and therefore one expects a lower availability of water for the deep rooted savanna trees at the beginning of the season.

Fig. 2 shows the soil temperature at 5 and 30 cm depth during the same period. The diurnal amplitude at 30 cm deep is considerably lower than at 5 cm, as expected. The data show an increase in the temperature near the surface during periods of limited moisture availability at all layers (e.g. from 280 to 295). The lack of percolation of water to the deeper layers, at the beginning of the period, affected the soil moisture storage (Scott *et al.*, 1997), and consequently the amount of water available to dissipate the incident energy.

To evaluate the relationship between the amplitude of the diurnal near-surface temperature cycle and moisture availability, we calculated the difference between the daily maximum and minimum temperature and plotted this against the soil near-surface moisture (see Fig. 3). The near-surface conditions are represented with data from 5 cm depth. We applied a 15-day moving average to the temperature amplitude data in order to remove high frequency variations due to factors besides soil moisture. Although soil moisture and soil temperature were not expected to be linearly correlated, the correlation coefficient was 0.87 (see Fig. 3 (b)). If the first 30 days of data are ignored, the coefficient increases to 0.95. This filtering seems reasonable since soil must settle around newly deployed sensors before the data become stable. This is because the presence of voids around the sensor rods reduces the measurement accuracy (Campbell Scientific, 1996).

Next, we analyzed the evolution of near-surface soil temperature with soil moisture content. Fig. 4(a1) and Fig.4 (b1) show an example for DOY 280 through 283. This corresponds to a dry (no rain) period. As the soil moisture decreases due to evaporation, the diurnal surface temperature range increases and becomes more pronounced. We looked at variables that tend to produce non-linear trends on near-surface temperature, such as wind and solar insolation. To assess the impact of these, we analyze data collected at the Skukuza meteorological site. The data show a persistence of mostly cloudy conditions (more than 50%), in the morning, on 54 out of 91 days considered in this study. Clear conditions throughout the day are only observed on 13. For DOY 282 and 283, considered above, no clouds were observed and wind conditions were average (2 m/s).

Figs. 4 (a2) and 4(b2) illustrate an example in which, although there is no significant variation in the soil moisture content, the amplitude of the diurnal temperature cycle varies greatly from day to day. The period corresponds to DOY 284 through 287. The cloudiness data presented in Table 2 suggest that DOY 285 and 286 were mostly cloudy. We hypothesize that the clouds prevented solar radiation from reaching the surface and emitted radiation from escaping to space. This would explain the decrease in the diurnal temperature amplitude on those days. The curve recovers the stress shape on DOY 287 on which cloudiness is very low.

These results support our hypothesis, namely that soil temperature is strongly related to soil moisture near the surface. However, the soil moisture in the deeper rooting zone, which determines vegetation water stress, may not be strongly related to surface moisture. Clearly, more data and use of sophisticated models of both soil and vegetation are required to relate surface temperature to water content at rooting depth. That is the focus of our current efforts.

CONCLUSIONS

The soil moisture and soil temperature data collected at the Skukuza site in 1999 appear to be highly correlated when a moving average of 15 days is applied, showing a correlation coefficient of 0.95 if the first month of data is ignored. We speculate that a 30-day period after deployment is required for the sensors to reach equilibrium with the surrounding soil. We also looked at the impact of fractional cloud cover and wind on near-surface soil temperature. During days of soil moisture deficit and high cloud cover, we observed a decrease in the diurnal temperature range. We explain that result as a consequence of the decrease in the amount of radiation reaching the surface and decreased cooling of the surface by emitted radiation exiting to space.

Our results were based on *in situ* data only. The remote estimation of surface temperature by satellite is naturally complicated by the heterogeneity of the surface. For bare soils, surface temperature is primarily a function of surface soil moisture. For a completely closed canopy (no gaps), the surface temperature primarily equals the canopy temperature. Higher than expected canopy temperatures are indicators of plant water stress. For example, Gaussman (1985) found cotton plant leaves were more than 6 ^{o}C above air temperature when they were severely water stressed. Increased leaf temperatures result from decreased cooling upon leaf stomatal closure (Jupp *et al.*, 1998). Stomatal closure is in part a function of the water available in the root zone, which may be well below the surface. Thus we must understand the relationship between stomatal conductance and soil hydraulic properties if we are to detect water stress from remotely sensed canopy temperature.

To learn about the combined thermal response from vegetation and bare soil, we are presently calibrating the SiB2 model for the southern African environment. Extensive ground data are being collected for this purpose. Measurements include CO2, water and energy fluxes, and will be coordinated with remote sensing measurements from the Advanced Very High Resolution Radiometer (AVHRR), EOS Moderate Resolution Imaging Spectrometer (MODIS), Enhanced Thematic Mapper Plus (ETM+) and EOS Advanced Spaceborne Emission Reflectance Radiometer (ASTER).

AKNOWLEDGEMENTS

We thank Ms. Birgit Bengis at Skukuza, South Africa, for the weather data and assistance in the field work. This project is part of the Southern Africa Validation of EOS (SAVE) project funded under the EOS Validation Program (D. Starr, Program Scientist).

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Table 1: Correlation coefficient between soil moisture (SM) and soil temperature (ST) in profiles A and B.

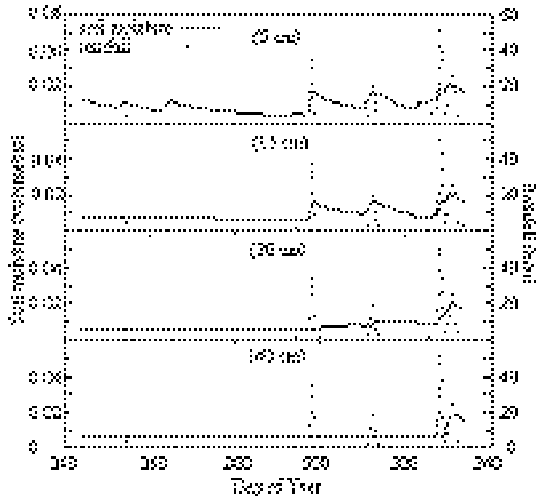
	Coef. Corr.
SM - 5 cm	0.996
SM - 15 cm	0.996
SM - 30 cm	0.909
ST - 5 cm	0.988
ST - 30 cm	0.949

Table 2: Cloud amount and wind velocity (DOY 280-287).

Day of the Year	Cloud amount* 08:00	14:00	20:00	Wind velocity (m/s)
280	7	4	6	5
281	8	5	0	3
282	0	0	0	2
283	0	0	0	2
284	0	0	0	3
285	8	8	8	5
286	8	8	1	3
287	1	0	0	2

* Scale: 0-8 **(the ski is divided in 8 parts and cloudiness is assessed)**

Fig. 1. Daily average of soil moisture and rainfall (profile B).



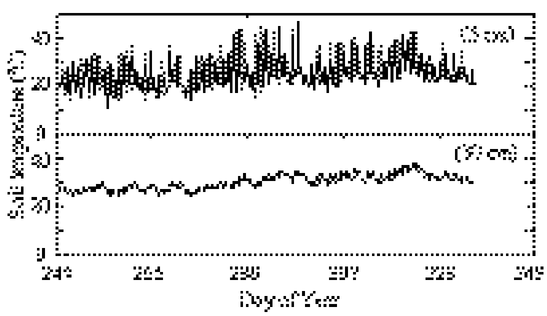


Fig. 2. Half-hour measurements of soil temperature at 5 and 30 (profile B)

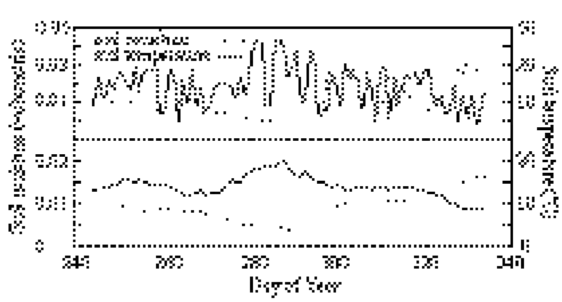


Fig. 3. Diurnal range of temperature variation (profile B)